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Abstract. A high resolution grating spectrometer (HRGS) with 2400 line/mm variable line spacing grating for the 10 – 50 Å wavelength range has been designed for laser–produced plasma experiments at the Lawrence Livermore National Laboratory (LLNL). The spectrometer has a large radius of curvature, R=44.3 m, is operated at a 2° grazing angle and can record high signal-to-noise spectra when used with a low-noise, cooled, charge-coupled device detector. The instrument can be operated with a 10 – 25 µm wide slit to achieve the best spectral resolving power on laser plasma sources, approaching 2000, or in slitless mode with a small symmetrical emission source. Results will be presented for the spectral response of the spectrometer cross-calibrated at the LLNL Electron Beam Ion Trap facility using the broadband x-ray energy EBIT Calorimeter Spectrometer (ECS).

1 Introduction

A high resolution grating spectrometer (HRGS) has been designed to make measurements of spectral line shapes as well as precise wavelength positions of highly ionized lines emitted from laser-produced plasmas [1]. For this study, the main lines of interest are the K-shell oxygen and carbon series lines in the 10 – 50 Å wavelength band. An important part of this work is to be able to diagnose the emission conditions of these plasmas, in particular the electron temperature T_e and density n_e. Several spectroscopic methods have been described that allow the determination of these plasma parameters [2, 3]. These include Stark broadening of the higher n transitions (for n_e), density-sensitive dielectronic satellite line intensity ratios, x-ray continuum slope (for T_e), resonance line intensity ratios in the He-like and H-like ion series (for T_e) as well as satellite to resonance line ratios (for T_e). Knowledge of the instrument spectral sensitivity response curve across the waveband is required to determine accurately some of the above electron temperature parameters. Previous work calibrating a 2400 line/mm flat field variable spacing grating spectrometer was achieved by observing a laser-produced plasma source simultaneously with a transmission grating spectrometer of known efficiency [4]. In this work we report the calibration of the HRGS instrument using the SuperEBIT electron beam ion trap x-ray source located at LLNL. The spectral sensitivity consisting of the grating reflectivity $R(E)$ and detector quantum efficiency $Q(E)$ are determined against the EBIT Calorimeter Spectrometer (ECS) [5]. The thin 200 nm aluminum foil filter used as a light tight filter in the laser plasma experiments is calibrated separately using the ECS and SuperEBIT [6].

In the next section the HRGS instrument, the SuperEBIT source, the ECS and the methods for calibrating the spectral sensitivity are described in detail. In section 3 the results of the measurements are presented and compared with other values in the literature.

2 Experimental Description

The high resolution grating spectrometer uses a large radius of curvature, R=44.3 m, 2400 line/mm variable-spaced grating as the wavelength dispersion element. The grating, with a large active area of 10 × 5 cm^2 (L × W), is inclined at an angle of incidence of approximately 2° to the source. The instrument is run on laser-produced plasma experiments with a 25 μm slit placed at 150 cm from the grating and defines the instrument spectral resolution. For the operation on SuperEBIT the slit was removed and the instrument was set up to focus onto the x-ray emission region of the ion trap. A low noise LN-cooled, back-thinned CCD 1300 × 1340 (20 × 20 μm^2 pixel) charge-coupled device records the spectrum and is located approximately 150 cm from the grating. This instrument is enclosed in a separate vacuum chamber and is bolted and aligned to the laser target or SuperEBIT x-ray source [1]. Single-shot spectra with lines resolved to about one part in 2000 are recorded from the laser-irradiated targets with energy on target of 0.5 J or more. For the SuperEBIT calibration runs the integration times were varied from 10 minutes to 60 minutes to record a spectrum with good line intensity. Figure 1 shows the layout of the HRGS instrument on SuperEBIT.

The LLNL EBIT-I was first built in 1986. SuperEBIT has been in operation for over 15 years [7]. It has been used to generate precise atomic data, detailed spectroscopy of highly charged ions as well as a calibration source for x-ray instrumentation. For this study neutral atoms using the gases CO_2, Kr, Ne, and SF_6, were injected into the trap and collisionally ionized by the electron beam. The beam electrons are confined and focused by a 3T magnetic field generated by superconducting Helmoltz coils. The ions are longitudinally confined by three voltages applied to the drift tube. Radial confinement is produced by the electron beam. This produces a trap dimension of 2 cm × 60 μm (H × W) where the electron density n_e is in the range 2 × 10^{10} – 5 × 10^{12} cm^{-3}. The ionization of the gas is adjusted by the electron beam voltage and the trap time defined by gating the drift voltages.

A second instrument very similar to the HRGS designed for use on EBIT used the same 2400 line/mm R=44.3 m, 2400 line/mm grating and a LN-cooled CCD as described above [8]. It was set up like the HRGS and run in the same way where the instrument was focused on the EBIT x-ray source.

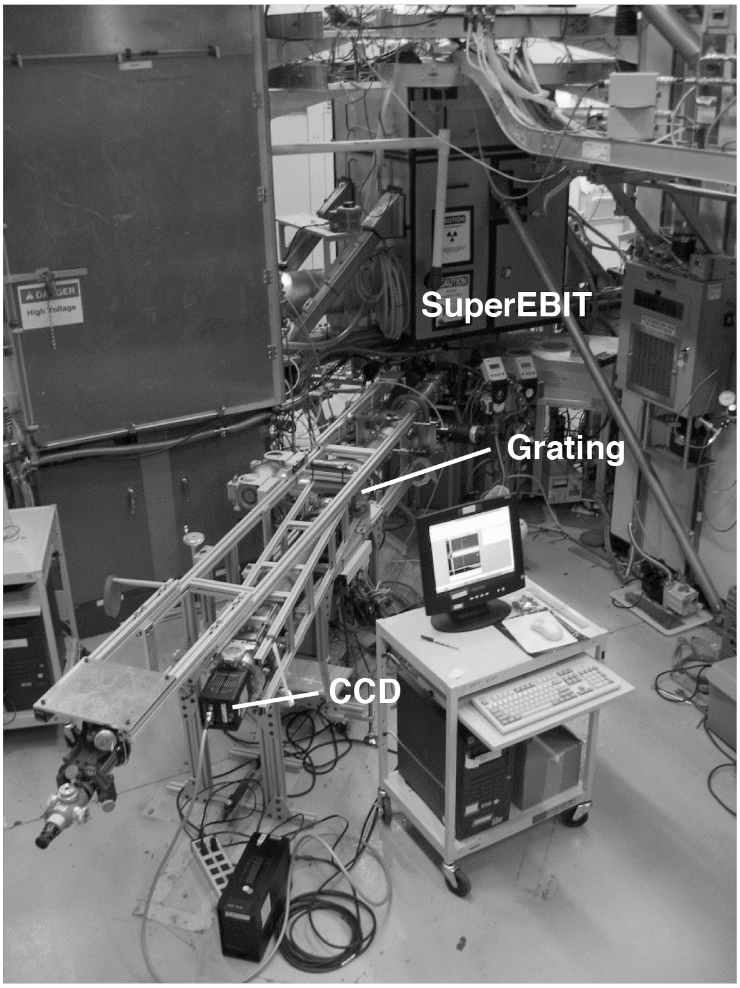

Fig. 1. High resolution grating spectrometer on the LLNL SuperEBIT. Grating and CCD detector are separated by 150 cm. Other instrumentation used in the experiment is located out of view on the opposite side of SuperEBIT.

The main calibration spectrometer, the EBIT calorimeter spectrometer (ECS), is a solid-state device first developed at NASA's Goddard Space Flight Center in 1984 [5]. The present ECS consists of a 6 × 6 array of HgTe pixels cryogenically-cooled to 50 mK using an adiabatic de-magnetization refrigerator in a liquid $^3He/^4He$ bath. The array consists of 625 × 625 μm^2 × 8 μm thick pixels for mid-energy 0.1 – 10 keV photons interspersed with 625 ×

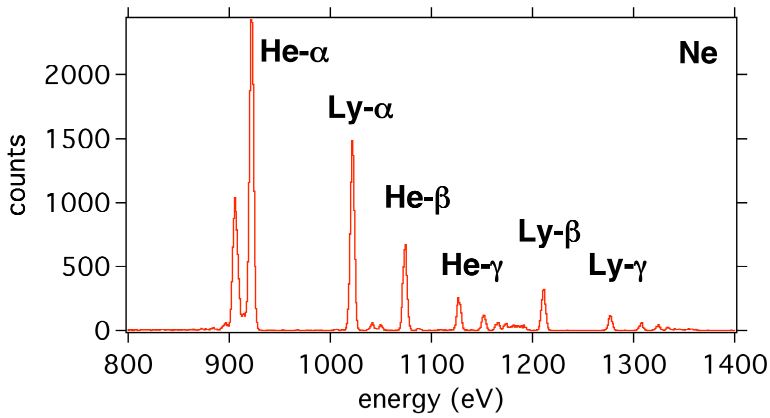

Fig. 2. Spectrum emitted from He-like and H-like Ne produced by SuperEBIT and measured with the ECS. Strongest transitions are labeled.

500 μm^2 × 100 μm thick pixels for high energy 0.5 – 100 keV photon detection. HgTe is chosen as the detector material because of high x-ray absorption and low heat capacity. X-ray absorption is 100% for photon energy below 4 keV. The energy resolution when operated at the 50 mK temperature is ΔE ~ 5 eV at 6 keV and ΔE ~ 25 eV at 60 keV photon energy. Thermal isolation of the calorimeter is achieved with 4 thin foils of aluminized polyimide ($C_{22}H_{10}N_2O_5$) with a total thickness of 143.4 nm Al/218.2 nm polyimide. The absorption of this filter set has to be corrected in the calibration for low energy photons under study here. A typical K-shell spectrum for Ne is shown in Fig. 2 where the x-ray photons are detected by

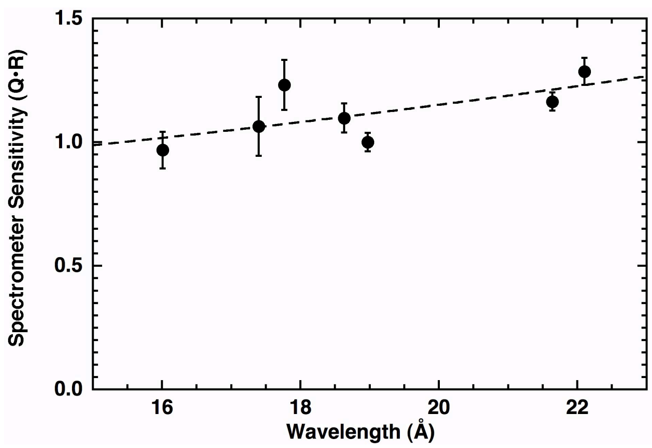

Fig. 3. Relative HRGS spectrometer sensitivity (detector efficiency and grating reflectivity) normalized against the oxygen Ly-α spectral line at 18.97 Å. Dashed line is second order polynomial fit to data points.

the mid-energy pixels in the ECS array. High n = 7 transitions can be clearly resolved in the He-like and H-like series where $E/\Delta E$ is 200 at 1 keV photon energy. For filter calibration, the filter was placed on a translation stage between the ECS and the x-ray source. Several runs of equal integration time were conducted with the filter in and out. The signal intensity and ionization balance of the x-ray source were monitored in all runs with the two grating spectrometers and the ECS data was corrected for small changes.

3 Experimental Results

A preliminary calibration of the relative sensitivity $Q(E)\bullet R(E)$ is determined for the HRGS by measuring the change in the sensitivity in the 15 – 23 Å range normalized to the O H-like $1s$ – $2p$ line at 18.97 Å. The integrated signal in the spectral lines was measured for both the ECS and HRGS instruments running and integrating x-ray signal simultaneously. The filter response of the ECS was corrected for in the number of detected photons to determine the photon fluence incident on the HRGS instrument. The photon energy in each spectral line was taken into account in the analysis of the HRGS results. Figure 3 shows the results of the relative spectrometer sensitivity for the HRGS. The dashed line is a quadratic fit to the data points.

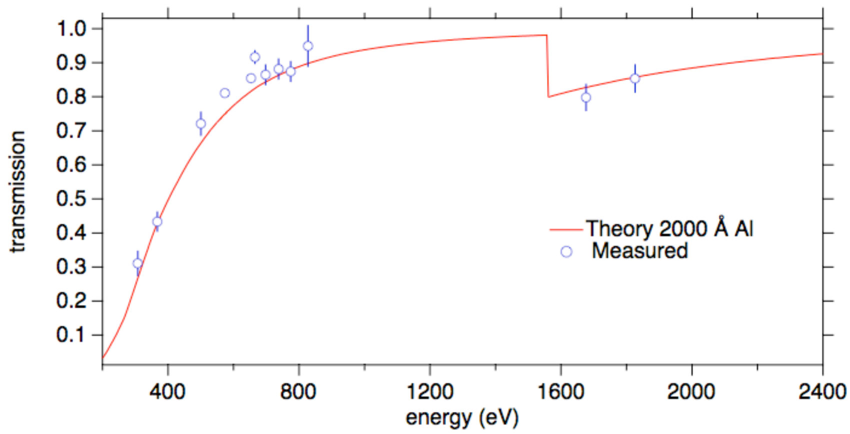

Fig. 4. Measured transmission of a 200 nm Al filter using the ECS. Solid line is theoretical data obtained from ref. 9.

Error bars are determined mainly by the photon statistics recorded in each line with the largest errors coming from the weaker, higher n transitions. There is a general trend of sensitivity falling by approximately 25% with decreasing wavelength largely from the grating reflectivity response. The reported reflectivity for a smaller radius of curvature 2400 line/mm Hitachi grating in the same waveband shows a more rapid fall off in reflectivity [4].

Figure 4 shows the spectrometer filter transmission for the 200 nm Al measured by the ECS as described in the previous section. Good agreement between the measured values and the predicted transmission curve [9] is shown for the energy range investigated here. The results presented in Figs. 3 and 4 indicate that the high resolution grating instrument response can be accurately calibrated on EBIT. The HRGS is found to have useable reflectivity to below 12 Å. More details of the calibration will be reported at a later date, including using the ECS for absolute efficiency calibration.

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